THE EFFECT OF ELECTROCHEMICAL MACHINING AND POST ECM SURFACE CONDITIONING ON FATIGUE

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A Thesis Submitted
in partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

by
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to the

DEPARTMENT OF METALLURGICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

C E R T I F I C A T E

This is to certify that this work 'The Effect of Electrochemical Machining and Post ECM Surface Conditioning on Fatigue' has been carried out by Mr. Amar Pal Singh Rana under my supervision and it has not been submitted elsewhere for a degree.

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SYNOPSIS

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The components of sophisticated design and the tough, heat resistant, difficult to machine metals and alloys, have provided the need and impetus for the development of new manufacturing techniques. As these new technologies reach maturity, all industries can look to them as means of improving their manufacturing efficiency. Electrochemical machining is one of these techniques; it offers a fundamentally different, effective, and economic alternative to mechanical methods of machining metals.

To study the effect of Electrochemical machining on fatigue, an apparatus which simulates the conditions encountered in actual ECM operation was developed for EC machining of cantilever fatigue specimens.

The ECM cantilever fatigue specimens were also developed. This compact simulation apparatus could be utilized at low electrolyte pressures and yet give rise to turbulent flow in the machining gap, a condition essential for ECM.

The design of the simulation appartus is simple in order to minimise the tooling cost and provides a positive location for the test specimen. This apparatus can also be used for EC machining of other mechanical testing specimens after simple modifications.

The statistical analysis of the fatigue data is complicated by the fact that we cannot measure the individual value of the fatigue limit for any given specimen. We can only test a specimen at a particular stress, and if the specimen fails, then the stress was some where above the fatigue limit of the specimen. Since the specimen cannot be retested, even if it "ran out" it is necessary to estimate the statistics of the fatigue limit by testing a large number of presumably identical specimens at different stress levels. Thus, near the fatigue limit, fatigue is a "go - nogo" proposition. "Stair case method" of statistically analysing fatigue data is used as it automatically concentrates testing near the mean, hence it increases the accuracy with which mean can be estimated, and with a fewer number of specimens.

If the functional operation of a component is such that its fatigue strength is important, then post ECM surface conditioning will be necessary. The fatigue strength of a EC machined surface can be raised to values equal to or greater than those displayed by conventional metal removal processes, by using simple finishing treatments. In this

analysis an entirely new approach was tried viz. Ultrasonics, in which the abrasive particles strike the specimen with impact forces upto 150,000 times their own weight.

It is thus concluded that:

(a) EC machining lowers the mean fatigue limit. In actuality, the process is only bearing the true fatigue properties of the base metal as EC machining gently removes the surface layers and leaves a stress-free surface. This apparent reduction arises from the usual comparison with specimens prepared by conventional machining process that generates a beneficial compressive stress on the surface.

(b) EC machining reduces the standard deviation. This emphasises that to study the effect of a variable on fatigue, the specimens should be EC machined for obtaining bonafide results, which can be compared without incorporating surface effects, thus revealing the effect of the variable only.

(c) Ultrasonics, as a post ECM surface conditioning process can restore the fatigue properties with the added advantage that complex shapes can be treated with ease. It can be easily controlled to give reliable, repetitive results.

CONTENTS

CHAPTER - 1

INTRODUCTION

The components of sophisticated design and the tough, heat resistant, difficult to machine metals and alloys, have provided the need and impetus for the development of new manufacturing techniques. Conventional methods of edge cutting tool practice are no longer adequate to meet all the requirements. Electrochemical machining is one of these techniques; it offers a fundamentally different, effective, and economic alternative to mechanical methods of machining metals.

1.1 Non-traditional Machining technologies

For convenience, let us group the various methods that appear to be presently feasible. In so doing we have four distinct groups of Non-traditional machining technologies. These are characterised by the fact that the rate at which metal can be removed by their use is independent of the hardness of the workpiece.

Group 1: Thermal methods of machining are based on the fact that, by concentrating energy on to a small area of the workpiece, the workpiece material can be melted or even vaporised. The energy may be supplied in the form of heat (flame or plasma torch cutting[1]), light (lasers[2]) or by electron bombardment (electron beam[3] and spark erosion[4]). The only one of the thermal methods that is capable of economically removing appreciable amounts of metal from a workpiece with reasonable accuracy is the spark erosion process.

Group 2: Dissolution by chemical action. In this group we have the well known chemical milling[5] techniques which, apart from applications such as printed circuitry, does not appear to have spread much beyond the aerospace industries.

Group 3: Electrochemical removal. Here we have electrochemical machining, and electrolytic grinding.

Group 4: Erosion and abrasive impact machining. In this group we find ultrasonic machining[6] and abrasive jet machining. Ultrasonic machining is the application of ultrasonics to excite abrasive particles on the workface, rather than the more popular concept of ultrasonically exciting the workpiece or tool in the traditional metal cutting art.

1.2 The Early History of Electrochemical Machining

The phenomenon of electrolysis was first studied scientifically more than 160 years ago and the intentional electrolytic removal of metals has been practised for many years in electropickling process which makes use of electrolytic action to remove surface films from metal products. Electrolytic polishing[7] was first developed by Jacquet in 1935 and is now widely used for the preparation of specimens for metallographic examination.

An electrochemical cutting off machine was described in 1946, but the application of electrochemical methods for actually machining seems to have been first put to general use about 1950 in form of electrolytic or electrolytically - assisted grinding[8]. The extension

to pure electrochemical removal of metal came eight or ten years later, with the development of electrochemical machines for drilling holes and shaping turbine blades.

However, electrochemical machining turns out to have been first proposed in 1929, when a Russian, Wladmir Gusseff, filed a patent for an electrochemical machining process with many features almost identical to the process as now practised. In USA, both Anocut and Battelle Memorial Institute worked along similar lines. Basically, their technique is to apply a constant voltage between two electrodes, keep the electrolyte at a constant temperature, have a constant feed rate between anode and cathode and pump the electrolyte at a constant high pressure in the machining gap, thus removing the products of electrolysis by high flowrates.

While these developments were going on in the period 1956-66 other organisations were approaching electrochemical machining by the route of electrochemically assisted grinding. Diamond-impregnated metal-bonded wheels were used, and by employing an electrically conducting electrolyte as 'coolant'. The protruding diamonds enabled some insulation to be established between wheel and workpiece, while maintaining a small working gap of only a few thousands of an inch. Early reports claimed that electrochemically - assisted grinding reduced wheel-wear to about one-third of what would have been expected in comparable conditions without the applied potential.

1.3 Scope and advantages of ECM

Electrochemical machine tools are expensive to buy and to operate; approximately 3 kwh are needed to remove one cubic inch of metal, whereas a conventional metal-cutting machine tool may require only 0.1 kwh if the material is readily machinable. But with electrochemical machining the rate of metal removal is, of course, independent of the hardness of the workpiece, and at present electrochemical machining is mainly used for the machining of materials which, because of their hardness or toughness, can be machined only very slowly by conventional methods. In these circumstances less energy is required to remove metal electrochemically than is required for conventional machining of very complex workpieces in relatively soft materials since with electrochemical machining in contrast to conventional machining, the whole surface of the workpiece can be machined simultaneously and the machining time required can be very much less than by conventional metal cutting. The scope for electrochemical machining therefore depends upon both the complexity of the workpiece shape and the hardness or toughness of the workpiece material. (Refer figure 1)

CHAPTER - 2

ELECTROCHEMICAL MACHINING

Electrochemical machining can be regarded as the reverse process to electroplating. Difference between electrochemical machining and other electrolytic processes, which has important practical and theoretical consequences, is the magnitude of the current densities employed. In ECM these may be as great as 800 A/cm^2 or about 1000 times greater than in electroplating or electrolytic pickling. With most metals and alloys ECM has a neutral effect on mechanical properties[9] such as yield strength, ultimate tensile strength, etc. However with metals and alloys such as beryllium and tungsten, the surfaces of which are apt to be damaged by conventional machining processes, ECM leads to markedly improved mechanical properties. The improvement results from the removal of damaged surface layers without the introduction of new stresses[10].

2.1 The ECM Cell

It is convenient to classify electrochemical reactions according to three locations at which they occur at the anode surface, at the cathode surface, and in the bulk of the electrolyte. The reactions vary depending on whether the electrolyte is acidic, neutral or basic.

In neutral or basic electrolytes the main reaction at the cathode is electrolysis of water, causing liberation of hydrogen gas and [illegible]

Anode reactions

As the metal dissolves from the anode, electrons are left behind at a rate dependent on the metal valency. Thus for an iron anode:

$$Fe \quad = \quad Fe^{2+} \; + \; 2e$$

This is the predominant reaction but may be accompanied to a very limited extent, by the hydrolysis of water and liberation of cation electric charge.

In the hydrolysis of water oxygen is liberated and hydrogen ions are formed, so that there is a local increase in electrolyte acidity.

$$2H_2O \quad = \quad O_2 + 4H^+ + 4e$$

Although occurring at a higher potential, the liberation of the cation electric charge, rather than liberation of oxygen, appears to occur more readily in ECM

$$2Cl^- \quad = \quad Cl_2 + 2e$$

Both the foregoing reactions represent ECM process inefficiency, 5 to 10%, and in the latter the loss of cations depletes the strength of the electrolyte.

Cathode Reactions

In neutral or basic electrolytes the main reaction at the cathode is electrolysis of water, causing liberation of hydrogen gas and local increased alkalinity because of the formation of hydroxyl ions:

$$2H_2O + 2e = H_2 + 2OH^-$$

Liberation of hydrogen, by neutralising the charge in hydrogen ions is the main reaction in acidic electrolytes.

$$2H^+ + 2e = H_2$$

Metal ions can also reach the cathode, particularly in acidic electrolytes and be deposited there.

$$Fe^{2+} + 2e = Fe$$

The deposit tends to adhere loosely and forms slowly if the electrolyte is weak in metal ions. That is why acid electrolytes used in ECM are frequently replenished, or a system, which periodically reverses the direction of the electrolysing current, is used to deplate the deposits that accumulate on the cathode. Even in neutral electrolytes, where metal ions form insoluble hydroxides, and are, therefore, not available in the vicinity of the cathode, a cathode deposit of about 0.001 in thickness does form during electrochemical machining. The effect is probably due to electrophoresis, in which suspended particles of metal hydroxides become positively charged, migrate to the cathode, and tend to be deposited there. By the same principle other particles in the electrolyte will tend to migrate to one or other electrodes. Small air bubbles, for example, will migrate to the anode, an effect which may explain the tendency of titanium anodes to passify with oxide films when machined using slightly aerated electrolyte.

Reactions within the Electrolyte

In neutral or basic electrolytes, metal ions leaving the anode surface progress outwards into the bulk of the electrolyte, where they combine either with hydroxyl ions or water molecules to form metal hydroxide that is usually insoluble.

$$Fe^{2+} + 2(OH)^- = Fe(OH)_2$$

$$Fe^{2+} + 2H_2O = Fe(OH)_2 + 2H^+$$

The immediate significance of these reactions is that the metal hydroxide can no longer play a significant role in the electrochemical reactions, so that plating out at the cathode, which is very undesirable, is avoided. Also, the precipitate can readily be removed from the electrolyte by centrifugal separation or gravitational settling so that the electrolyte basically remains unchanged by the process. The ferrous hydroxide so formed may then, quite independently of the electrochemical process, react further with water and dissolved oxygen or oxygen from air to give ferric hydroxide

$$4Fe(OH)_2 + 2H_2O + O_2 = 4Fe(OH)_3$$

Thus in the removal of 1 cm^3 of iron (7.85 g), 6.3g of water are drawn from the solution and 15 g of ferric hydroxide are produced. The ferric hydroxide produced in the removal of 1 cm^3 of iron has a volume (dry) of about 4 cm^3. In the wet state, however, the volume of the settled sludge is about 300 cm^3 of the 6.3g of water, 0.28g is liberated as hydrogen which, at normal temperatures and pressures, occupies a volume of 3 litres.

2.2 The operating voltage

Theoretically, only a few volts are required for metal transfer in an ECM cell. In practice this results in a very small working gap when high feed rates are used on large work these small gaps do not permit adequate electrolyte flow to remove the volume of reaction products created by firstly high current densities and secondly, the longer flow paths then encountered. Since the equilibrium gap increases with increase in applied voltage, and is inversely proportional to the feed rate, larger gaps can be achieved by using either higher voltages or slower feed rates. High feed rates are often required if full use is to be made of available current on high-powered machines. The large working gaps necessary to maintain continuous machining can then only be obtained by using high voltages.

Existing power units supply current at upto 15V. This has proved to be inadequate in certain cases, and it is necessary that larger power units should be built to supply current with a voltage range of 4 to at least 20V. If this higher voltage is not available the advantage of heavier currents will be lost to lower feed rates, low plant utilisation, and higher labour costs.

2.3 Spark detection systems

A spark detection device is an essential part of an ECM power unit. If a spark is allowed to develop, both tool and workpiece can suffer serious damage. The tool may be made of an alloy such as copper-tungsten, which is more resistant to spark erosion but even then,

the cost of damaged workpiece itself may be quite considerable. Strictly, a spark cannot be tolerated, particularly towards the end of the operation, because of the depth of the damage that can result from a fully developed work.

Arcing between the tool and the workpiece may occur for a number of reasons, but chiefly due to metal particles which may find their way into the gap. Another cause, which is more frequently encountered during the development of a new tool, is local electrolyte starvation. Sufficient electrolyte must be available over the whole area of the electrode to carry away the products of the reaction. Hence, more than one duct may be required in an ECM tool. Ram & Singh[11] have developed a mathematical method to calculate critical inter-channel spacing in ECM tool for adequate electrolyte in the machining gap to avoid striations and improve surface finish. If local electrolyte starvation takes place due to uneven flow distribution, local peaks in the workpiece may occur, resulting in gaps sufficiently small to initiate a spark.

A number of spark detection devices have been constructed; perhaps the most effective are those which become operative when the current rises or falls at beyond a preset rate, irrespective of the level of current used, since a spark can develop at any current level. The usefulness of the falling current aspect of the device is appreciated in two cases. The workpiece surface may passivate due to inadequate electrolyte flow, resulting in a decrease in the current passing through the gap. If the feed is not gap controlled, contact between

the two electrodes would then take place. Secondly, in a trepanning operation, the current naturally falls towards the end during the break-through since less work-piece area is exposed to the tool. The device can then be made to switch the machine off just before complete penetration.

The speed of response of a spark-detecting device is a vital characteristic, faster ones naturally reduce the degree of damage. The speed of response is more dependent on the characteristics of the power unit itself and for a saturable reactor, the time required to switch off the current is 5-6 cycles or some 100 ms. A silicon controlled rectifier (SCR) is capable of switching off in half a cycle or 10 ms. However, SCR's are more expensive and they are not generally available for the supply of heavy currents.

2.4 ECM Tooling

Tool design

The art of ECM is in the design of cathode tool, which is shaped to carry the electric current to the areas to be machined and has provision for the supply of an adequate and smooth flow of the electrolyte. It is also required, by definition, to produce the required shape in the workpiece. The word 'art' is used advisedly since tool design is based mainly on experience and a feel for the current and electrolyte distribution.

As an example consider a tool with three plane regions inclined at 0°, θ and 90° respectively to the feed direction. (Figure-2). The appropriate equilibrium gap is y_e when the surface of the tool is normal to the feed direction, and $y_e/\cos\theta$ for the inclined surface. This section of the workpiece will thus have an approximately parabolic shape.

The electrolyte is usually supplied to the machining gap through channels in ECM tool. To supply sufficient quantity of electrolyte to the gap, more than one channel is sometimes necessary. The critical interchannel spacing can be calculated mathematically [11].

Tool manufacture

If a single tool is required, it can be manufactured by conventional metal-cutting methods. However, it is advisable to have more than a single tool for a given operation as an insurance against accidental damage. Also, if the insulation fails, the tool will have to be repaired and unless a second tool is available, the production run would be interrupted, one method of producing a number of copper tools is to cold forge them using a hardened steel former. This approach is particularly suited for shapes that would otherwise require internal cavity machining.

Electroforming has been used successfully in the manufacture of small and large tools. This is an obvious way of tool manufacture which will find increasing application as the use of ECM becomes more

widely spread. The number of components to be machined is obviously an important factor, and high tooling cost is often offset by long production runs.

Insulation coatings

ECM cathodes have to be coated with an insulating material to prevent the flow of current from surfaces outside the working zone. The coating must adhere well and be resistant to chemical attack and erosion by the fast flowing electrolyte. Proprietary epoxy materials are available and are generally used, but it has been found in practice that they have a limited life and the tools have to be recoated, in some cases, as often as every ten operations. The problem is most severe in cases where a thin coating is necessary.

2.5 Electrolyte Processing

The metal removed from the workpiece is deposted as a hydroxide precipitate in the electrolyte. If the amount of metal removed is comparatively small, then there is little problem in disposing of the used up electrolyte. However, when large quantities are involved the problem becomes serious and positive measures have to be taken to satisfy a number of requirements.

The simplest method of separating the deposit from the electrolyte is to use static settling tanks. This is quite adequate

provided there is sufficient space for the large number of tanks required for a given throughput. The settling process, however, is quite slow, although it can be accelerated chemically. The sludge is likely to have a high content of water when collected from the tanks, and a further drying operation becomes necessary. Naturally, this approach can not be regarded as a continuous method.

Centrifuges are perhaps the most effective way of separating the deposit. They can be operated on a continuous basis, and the residue has a lower moisture content than that obtained from settling tanks. Considerably less space is required, and a large centrifuge can cope with the output of three or four machines. Nevertheless, it can not be claimed that the problem is completely solved and other methods have to be developed to deal with this problem.

CHAPTER-3

FATIGUE TESTING

3.1 Introduction

Endurance limit or fatigue limit is defined as the stress level at which a fatigue failure occurs for a large number of cycles. Fatigue test at low stresses are usually carried out for 10 million cycles and sometimes 500 million cycles for non-ferrous metals. The results of fatigue testing are summarized in the form of well known S-N curve.

Unlike the case of tensile testing wherein yield strength can be determined from a single specimen and the mean and standard deviation by conventional methods by testing groups of specimen, it requires lots of samples to plot a single S-N curve. Hence the standard deviation in the fatigue testing cannot be determined by conventional methods. Conventional methods cannot account for run out samples as they are supposed to have infinite lives. First let us discuss a few other examples which have much in common with fatigue testing.

(a) In quality control laboratory of an explosives manufacturing firm, a common procedure is to drop a weight on specimens of the same explosive mixture from various heights. There are heights at which some specimens will explode and other will not, and it is assumed that those which will not explode would explode were the weights dropped from a sufficiently greater height. It is, supposed, therefore, that there is a critical

height associated with each specimen, and that the specimen will explode when the weight is dropped from a greater height and it will not explode when the weight is dropped from a lesser height. The population of specimens is thus characterized by a continuous variable—the critical height— which cannot be measured. All one can do is to select some height arbitrarily and determine whether the critical height for a given specimen is less than or greater than the selected height.

(b) This situation arises in many fields of research. Thus in testing insecticides, a critical dose is associated with each insect, but one cannot measure it. One can only try some dose and observe whether or not the insect is killed, that is, observe whether the critical dose for that insect is less than or greater than the chosen dose. The same difficulty arises in research dealing with germicides, anesthetics and in testing strength of other drugs, in psycho-physical research dealing with threshold stimuli and in several areas of biological and medical research[12].

Such experiments are called sensitivity experiments and it is not possible to make more than one observation on a given specimen once a test has been made the specimen is altered (the explosive is packed, the insect is weakened, fatigue specimen undergoes coaxing) so a bonafide result cannot be obtained from a second test on that specimen.

It should be recognized that each specimen has its own fatigue limit, a stress above which it will fail but below which it will not fail and that this critical stress varies from specimen to specimen

for very obscure reasons viz, inclusion content, dislocation geometry, surface finish, etc, even if the specimens are made from same bar stock. The statistical problem of accurately determining the fatigue limit is complicated by the fact that we cannot measure the individual value of the fatigue limit for any given specimen. We can only test a specimen at a particular stress and if the specimen fails, then the stress was somewhere above the fatigue limit of specimen. The specimen cannot be retested even if it did not fail at the test stress. Thus near fatigue limit, fatigue is a "go-nogo" proposition.

3.2 <u>Stair Case Method</u> [13]

This method requires some conditions to be fulfilled: In the first place, the analysis requires that the variate under analysis be normally distributed. If this is not the case the variate be transformed to one which does have the normal distribution. If one has no idea of the shape of his distribution function then the data of the experiment itself must be used to provide this information. The common procedure is to compute the percentage affected at each level and plot this percentage against various functions of the variate in question. Usually one can soon discover what sort of function will force the percentage to be normally distributed. There are, of course, infinitely many functions to choose from; the criteria is that the chosen function be as simple as possible consistent with whatever knowledge is available concerning the nature of the material at hand.

Fatigue limit is reported in terms of "stress value" or in terms of "fatigue life". There is absolutely no dirth of data in each. If data is reported in "stress value" it is normally distributed and if data is reported in terms of "fatigue life (say N)" then log N is normally distributed. Let us study the following example. (Figure 3)

The first specimen is tested at the estimated value of fatigue limit. If this specimen fails the stress for next specimen is decreased by a fixed amount. This procedure is continued for each succeeding specimen until a run out is obtained. The stress applied to next specimen is then increased by the increment. This procedure is further continued, the stress being increased when specimen runs out and decreased when it fails. Fifteen to twenty five specimens must be tested. As this process is random we should expect number of failures = number of non-failures (run outs). In fact, the number of failures at any level cannot differ by more than one from the number of successes at the next higher level due to the way the test is conducted.

This analysis is based on the less frequent interval. Hence in this example only 'run outs' are considered. To determine the mean fatigue limit, the data are arranged in a tabular form as in Table 1. The lowest stress level at which a nonfailure is obtained is denoted by $i = 0$, and next $i = 1$ etc. The mean fatigue limit '$\bar{F}$' and

its standard deviation 'S' are determined from Eqs. (3-1) & (3-2). The constants in these equations are explained in Table 1. (Figure 3)

The positive sign is used in Eq. (3-1) when the analysis is based on non-failures, while the negative sign is used when it is based on failures.

(mean) $$\bar{X} = X_o + d\left(\frac{A}{N} \pm \frac{1}{2}\right) \qquad (3\text{-}1)$$

(S.D.) $$S = 1.620d\left(\frac{NB-A^2}{N^2} + .029\right), \text{ if } \frac{NB-A^2}{N^2} > 0.3 \qquad (3\text{-}2)$$

Analysis is simple if these testing levels are equally spaced. One must be able to estimate roughly in advance the S.D. of the normally distributed transformed variate. The interval between testing levels should be approximately equal to the standard deviation. This condition is well enough satisfied if the interval actually used is less than twice the S.D. This requirement is not severe, for research workers who repeatedly perform these experiments on essentially similar materials can usually make very good preliminary estimates. The testing levels should be quite small for maximum precision in the mean, but in practice this is not true for several reasons. In the first place the curves are for expected values and essentially assume infinite sample numbers and in fact very large number of samples are required to get a good estimate of the mean for ~~a very required to get a good estimate of the mean for~~ a very small interval. This estimate may be biased appreciably toward the initial

testing level unless the sample is very large. ~~Secondly, a small interval level unless the sample is very large.~~ Secondly, a small interval may cause one to waste observations unless a good choice for the initial level is made. If the poor choice is made many observations must be spent getting from that level to the region of the mean. Any way this is not reflected in the analysis, because number of run outs will be less, hence the analysis will be based on runout data. Finally the precision of the mean must actually be measured by standard deviation and the accuracy of standard deviation becomes poor for very small intervals.

Advantages:

1. The statistical analysis is quite simple, whereas the analysis of ordinary method which involves testing of a large number of presumably identical specimens at different levels is rather tedious.
2. The primary method of this method is that it automatically concentrates testing near the mean, hence it increases the accuracy with which the mean can be estimated. Alternatively, for a given accuracy this method requires fewer tests than the ordinary method of testing groups of equal size at preassigned levels. The saving in the number of observations may be of the order of 30 to 40%. Though this method is particularly effective for estimating the mean, it is not a good method for estimating small or large percentage points, e.e. extreme points, viz, where 1% of specimen fail. The design

engineer is usually interested in establishing the smallest values of property being tested, so that the design can be based on conservative yet realistic values. For example, the designer might be interested in knowing the value of fatigue limit where 1% of specimens fail, while a metallurgist is mainly interested in mean & standard deviation of his test values. The reason is that no method which uses the normal distribution can be relied on to estimate extreme % points because such estimates depend critically on the assumption of normality. In most experimental research, it is possible to find simple transformations which make the variate essentially normal in the region of the mean, but to make it normal in the tails is quite another matter. Nothing short of an extensive exploration of the distribution involving perhaps thousands of observations will suffice here ( ). Alternative approaches have been the use of extreme value distribution or Weibull's distribution .

This method has one obvious disadvantage in certain kinds of experiments because it requires that each specimen be tested separately. This is important in fatigue testing where each test must be made separately anyway. But in tests of insecticides, e.g., a large group of insects can sometimes be treated as easily, as a single one and in large experiments of this kind any advantage of this method might well be outweighed by this requirement of single tests. Even here if expensive samples were being used, the advantage in economy of tests might the trouble of making single tests.

Another disadvantage is that the tests must be run in a sequence.

CHAPTER 4

EXPERIMENTAL PROCEDURE

4.1 ECM cantilever fatigue test specimen

A conventional cantilever fatigue test specimen is shown in Figure 4. ECM cantilever fatigue test specimen should be designed to meet the following requirements:

(a) It should be symmetric about y axis, so that the current distribution is uniform throughout.

(b) The surfaces to be EC machined must be slightly oversize (about 0.02" in diameter) than the conventional specimen so that after EC machining, it is as close as possible to the conventional specimen for ease of testing.

(c) Finally the EC specimen must be geometrically similar to conventional cantilever fatigue specimen for a comparasion to be made in fatigue properties.

The EC cantilever fatigue test specimen designed to meet all the above requirements is shown in Figure 5. The area to be machined electrochemically is required for calculation of current density. This is shown in Figure 6.

Machining area = $A_1 + A_2$

$A_2 = 2\pi rh = \pi dh$

where h = length (3.5") of A_2

r = radius of A_2

d = diameter of A_2 (0.25")

Hence $A_2 = 2.75 \text{ in}^2$

<u>Calculation of A_1</u>

The equation of ~~will~~ circle shown in Figure 6 is:

$$(x - 0.3875)^2 + (y - 0.625)^2 = 0.25 \qquad (4-1)$$

Put $x - 0.3875 = - 0.5 \cos\theta$

$y - 0.625 = - 0.5 \sin\theta$

$dx = 0.5 \sin\theta . d\theta$

$dy = -0.5 \cos\theta . d\theta$

$ds = dx^2 + dy^2 = 0.5 d\theta$

$$A_2 = \int 2\pi y ds = \int_{\theta_1}^{\pi/2} 2\pi(-0.5\sin\theta + 0.625)\, 0.5\, d\theta$$

$$= 0.5 \cdot 2\pi \cdot \int_{\theta_1}^{\pi/2} (0.625 - 0.5 \sin\theta)\, d\theta$$

$$= (0.625\theta + 0.5\cos\theta) \Big]_{\theta = 0.604}^{\theta = \pi/2}$$

$$= 0.52 \text{ in}^2$$

Hence Machining area $= 2.75 + 0.52 \text{ in}^2$

$= 3.27 \text{ in}^2$

4.2 EC cantilever fatigue specimen machining apparatus

A specialised EC cantilever fatigue specimen machining equipment must meet the following requirements:

(1) It must simulate the conditions encountered in commercial EC machining.

(2) It should be simple in construction and easy to fabricate.

(3) It must provide a positive location for the test specimen to avoid short-circuiting.

(4) It should be static in operation.

(5) Reynolds number must exceed 2000 for turbulent flow in the machining gap to remove the ions which have taken part in the reaction.

A compact, static, specialised equipment designed solely for EC machining of cantilever fatigue test specimens is shown in Figure 7.

Construction

It utilises the 'split aluminium cathode' principle for enveloping the specimen. The machining gap is 0.075". This is to fit accurately in the outer hollow aluminium cylinder (5) of rigid construction, to minimise contact resistance. The length of the split cathode (2) has to be chosen so that there is no possibility of short-circuiting. It contains channels at either end for adequate electrolyte flow. Further the channel for electrolyte inlet has to be kept longer in size than channel for electrolyte outlet to exert back pressure for

maintaining adequate electrolyte in machining gap for improved surface finish. After loading the EC fatigue specimen (1), the split electrodes (2) are held in position by brass nuts and bolts (6). The negative of the DC power supply is connected to these nuts and bolts (6).

The two specimen holders (3 and 4) shown exaggerated in Figure 7 are made out of an insulating material, perspex in this case. The diameter D_A & D_B have to be machined accurately so as to fit well in the outer aluminum cylinder (5) and the fatigue specimen (1), otherwise there will be leakage when electrolyte flows at considerable pressure in the machining gap. Diameters D_C for the specimen holder (input) is slightly smaller than diameter D_C' for specimen holder (output) for the same reasons as for channels in split electrode.

The inlet (9) and outlet (10) for electrolyte flow correspond to diameters D_C & D_C' of specimen holder. Here again the internal diameter of inlet tubing (9) is larger than that of outlet tubing (10) for same reasons as for specimen holder and channels in split electrode (2).

The covers (7) are again made of some insulating material (perspex in our case). These covers can be tightened to the ends of the cylinder by four bolts (11). They have a brass nut & bolts (8) at their center which is connected to positive of D.C. supply. These brass bolts are tightened so that they make good contact with the test specimen (1).

The design shown is simple in order to minimize the tooling cost and provides a positive location for the test specimen.

Working

The EC cantilever fatigue test specimen (1) is enveloped by the split aluminum cathode (2) with the wider channel towards face 1 of the specimen. It is inserted in the aluminum cylinder (5) with face 1 towards the input electrolyte tubing (9). The specimen holder (3) with diameter D_s is fitted onto face 1 of the specimen and specimen holder (4) is fitted to face 2 of specimen. The covers (7) at either end are tightened. The brass bolts (8) are tightened on both sides. The split anode is tightened on its place with bolts (6) provided. Electrolyte is forced in the machining gap by a suitable pump. Electrolyte from outlet end (10) flows back to the tank & hydrogen evolved escapes in the atmosphere. The hydroxide formed is collected at the bottom of the tank.

4.3 Post ECM Treatments (14,15)

If the functional operation of a component is such that its fatigue strength is important, then post ECM surface conditioning will be necessary. The fatigue strength of a properly EC machined surface can be raised to values equal to or greater than those displayed by mechanical metal removal processes, by using simple finishing treatments. One can select the most suitable post ECM treatment and put a firm value on fatigue strength. The following processes have all proved effective in suitably conditioning the surface of EC machined metals.

- Glass ball peening
- Barreling
- Grit air blasting
- Vibropolishing
- Vapour boring
- Mechanical polishing

All the processes provide some mechanical working on the surface and induce compressive stresses[16]. Some also remove a small layer of surface material. They are processes that are easily controlled to give reliable, repetitive results and are of course widely used in industry.

In this thesis work "Ultrasonic" has been used as a post ECM surface conditioning method to restore the fatigue properties. The basis of the ultrasonics is a property possessed by many metals to varying degrees and by a few to a marked degree. It is called magnetostriction and results in the contracting of metal when placed in a magnetic field. Each time the field reverses, the metal will contract or return to its norm.

The ultrasonic process simply causes the magnetic field to reverse at a frequency which being above 16,000 times per second, places it in what is termed the ultrasonic region, i.e., the vibrations are inaudible to human ears. The ultrasonic transducer is the mechanism by which this movement is produced so that it can be used to do work.

In principle, electro-mechanical transducer converts alternating electrical current, supplied by a Driver unit, into mechanical vibrations at 25,000 cycles per second, above the range of the human ear. Mechanical vibrations of the transducer are amplified and transmitted to the tool by means of "mechanical amplifiers" which are the transducer and tool.

The EC machined test specimens were ultrasonically treated by Fisher Ultrasonic Generator Model 3.6, Serial No. 167-205 at 900 watts using minus 150 mesh (tyler screen) alumina and water upto 5". The ultrasonic generator was put on for 15 minutes. The samples were subject to impact forces upto 150,000 times the weight of abrasive particles in the slurry.

Unlike other post ECM surface conditioning methods ultrasonics is safe; there are no hazardous moving parts or exposed electrical circuits. Ultrasonics, as a post ECM treating method can be easily controlled to give reliable repetitive results.

4.4 Fatigue Testing

Lathe machined, EC machined and EC machine + ultrasonically treated cantilever fatigue test specimens were obtained from the same mild steel rod (0.75" diameter) to study the effect of EC machining and ultrasonics alone. All other variables were kept constant. All these specimens were tested by stair case method (section 3.2).

The cut-off limit was set at 1.5×10^5 cycles. As an estimate of standard deviation is required in advance for determining

the stress increment, the standard deviation in case of conventionally machined specimens is available in literature. For EC machined & EC machined + ultrasonically treated specimens, a trial run was made with a few samples to have a rough estimate of the standard deviation.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Electrolyte flow

As already mentioned, unless there is violent agitation of the solution, there will be a concentration or depletion of ions near the surface of the electrode, and the rate of reaction is governed by the diffusion of ions up to or away from the electrode. The character of fluid flow in channels is determined by a dimensionless quantity R, the Reynolds number, which is given by

$$R = \frac{\rho V L}{\mu}$$

where ρ = density of fluid (1 gm/cc)

V = fluid velocity

μ = viscosity of fluid (1 centipoise)

L = characteristic length (machining gap 0.19 cm)

Calculation of fluid velocity in machining gap: It is difficult to directly measure the velocity of electrolyte in the small machining gap. However one can calculate it from flow measurements and cross sectional area through which electrolyte is sent.

Flow rate = velocity x Annular area of machining gap.

and Annular Area $= \frac{\pi}{4}\left[(0.04)^2 - (0.25)^2\right] (2.54)^2 \text{ cm}^2$

$$= \frac{\pi}{4} (2.54)^2 (0.0975) \text{ cm}^2$$

Flow rate = 63.2 cc/sec

Hence $63.2 = v.\ \frac{\pi}{4}(2.54)^2\ (0.0975)$

or $\quad v = 127.8$ cm/sec

Hence Reynolds number, R = 2425

This value of Reynolds number indicates that the flow in the machining gap is turbulent. For values of R less than 2000 any initial disturbance is rapidly damped out and the flow is laminar. In laminar flow the direction of flow of all particles of the fluid is essentially the same; the fluid in contact with the tool or workpiece at the entry to the gap remains in contact throughout the gap. Clearly, therefore, for practical electrochemical machining turbulent flow is necessary to remove or replenish at the electrodes the ions which have taken part in the reactions there. Further a high flow rate is required to keep the temperature of electrolyte within reasonable limits. Because the conductivity of electrolytes is temperature-dependent, an excessive temperature rise would lead to uneven machining.

5.2 Machining Rate

The EC machining of EC cantilever fatigue specimens was carried out at 9 volts using commercial sodium chloride solution as electrolyte with small percentages of potassium chromate and sodium benzoate to protect it from corrosion. The machining conditions were so adjusted to have a turbulent flow in the machining gap (Reynolds number 2425).

an essential requirement for ECM. Rough machining was done at 25 A.D.C. using Lambda Regulated D.C. Power supply Model LK 104-FM for 3½ minutes to remove the bulk material electrochemically. The final finishing was effected at 7.5 A.D.C. for 1½ minutes. The EC fatigue specimen was cut at section A-A and now it is equivalent to the conventional cantilever fatigue specimen.

The EC metal removal of fatigue specimens was upto a depth of 0.01" only. Hence to calculate the machining rate with better accuracy the hydroxide was collected for a given time. This is because for removal of 1 cm^3 of iron, the volume of the settled sludge is about 300 cm^3 thereby increasing the accuracy. This sludge was chemically analysed for total iron content as it may consist of mixture of ferric and ferrous hydroxide. It was found it contains 56.4% iron.

$$\text{The process efficiency} = \frac{\text{actual metal removal rate}}{\text{Theoretical \quad " \quad " \quad "}} \times 100$$

The theoretical metal removal rate of EC machine capable of supplying 'I' A.D.C. is $\frac{27.92 \times I \times 60}{96,500}$ g/min

The results are summarised in Table 2.

For low current densities, more time was allowed for hydroxide collection in order to collect reasonable quantity of it for better accuracy and at high current densities the hydroxide was collected for 1 minute for determining machining rate as large amounts of hydroxide is formed at high current densities.

Table 2. EC cantilever fatigue test specimen machining data

Salt conc., $g.lit^{-1}$	Current, A.D.C.	Current density $A.\ in^{-2}$	Machining time, min	Wt. of hydroxide g.	Wt. of Iron per min, $g.min^{-1}$	Theoretical rate, $g.min^{-1}$	Process efficiency %
1.25	4	1.22	5	0.598	0.067	0.069	97.2
2.50	6	1.84	3	0.537	0.101	0.104	97.1
4.56	10.5	3.21	2	0.628	0.177	0.182	97.1
6.25	14	4.28	2	0.835	0.236	0.243	97.1
8.75	18.5	5.66	1.5	0.611	0.305	0.321	95.1
9.62	20	6.11	1	0.585	0.331	0.347	95.1
10.10	22.5	6.88	1	0.658	0.371	0.391	95.1
12.50	25	7.65	1	0.731	0.412	0.434	95.0

Inefficiency, in terms of metal removal, is due to the following reasons

(a) Liberation of gas at anode, such as chlorine when using sodium chloride electrolyte

(b) I^2R losses

(c) hydrogen evolution

(d) Metal ions can also reach cathode particularly in acidic electrolytes and be deposited there. The deposit tends to adhere loosely and form slowly if the electrolyte is weak in metal ions. That is why acid electrolytes used in ECM are frequently replenished, or a system, which periodically reverses the direction of the electrolysing current, is used to deplate the deposits that accumulate at the cathode. Even in neutral electrolytes, where metal ions form insoluble hydroxides and are, therefore, not available in the vicinity of the cathode, a cathode deposit of about 0.001 in. thickness does form during electrochemical machining. The effect is probably due to electrophoresis, in which suspended particles of metal hydroxides become positively charged, migrate to the cathode, and tend to be deposited there. By the same principle other particles in the electrolyte will tend to migrate to one or other of the electrodes. Small air bubbles, for example, will migrate toward the anode, an effect which may explain the tendency of titanium anodes to passify with oxide films when machined using slightly aerated electrolyte.

(e) Effect of alloying elements not considered for calculation of theoretical metal removal rate.

Effect of current density on metal-removal rate

Increase of current density involves increase of overvoltage and may also involve an increase in one or other discharge potentials to permit a second reaction to proceed. Thus, in electrochemical machining of steel with sodium chloride solution as the electrolyte, the first reaction to take place at anode is dissolution of the workpiece. Whilst this process proceeds with 100% current efficiency, the rate of machining can be calculated from Faraday's laws. As the current density is increased however, the anode potential is raised sufficiently to allow evolution of oxygen. Some of the current through the cell is then associated with evolution of oxygen at the anode and in terms of removal of metal from the anode, the current efficiency is no longer 100%. Actually the overvoltage for the evolution of oxygen increases so rapidly with increase in current that the discharge potential of chloride ions is soon reached and so chlorine is also produced. The rate of metal removal thus increases with current density in the manner shown in Figure 8. In practice, current efficiencies of 75-90% are usual for electrochemical machining.

9.3 Fatigue testing results

The results of the stair case method for

(a) lathe machined specimens,

(b) EC machined specimens and

(c) EC machined specimens and ultrasonically treated specimens are summarized in Figures 9, 10 & 11 and Tables 3, 4 & 5. The cut off limit was set at 1.5×10^5 cycles. An estimate of standard deviation in case (a) is obtained from literature. In case (b) & (c), a trial

run was made with a few samples to have a rough estimate of the standard deviation. Since the analysis is based on the least frequent event (failures or nonfailures), only the nonfailures are considered. The lowest stress level at which a nonfailure is obtained is denoted $i = 0$, the next $i = 1$, etc. The mean fatigue limit $\bar{X}$ and its standard deviations are determined from Eqs. (3-1) & (3.2) (Section 3.2). The constants in these equations are explained in tables 3, 4 & 5.

Table 4 suggests that EC machining lowers the mean fatigue limit by 16.4%. However it must be remembered that conventional metal removal processes impart compressive stresses to the surface layers and these raise the fatigue strength. In contrast ECM removes stressed layers and leaves a stress-free surface that allows a true fatigue strength for the metal to be measured, uninfluenced by surface effects produced by a particular machining operation.

Further the standard deviation is also reduced which is attributed to the stress free surface obtained EC machining.

Table 5 suggests that ultrasonics as a post ECM treatment can restore the fatigue properties of EC machined specimens with the added advantage that complex shapes can be treated with ease. It can be easily controlled to give reliable, repetitive results.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

(1) Electrochemical machining lowers the mean fatigue limit. In actuality, the process is only bearing the true fatigue properties of the base metal as EC machining gently removes the surface layers and leaves a stress-free surface. This apparent reduction arises from the usual comparasion with specimens prepared by conventional machining process that generates a beneficial compressive stress on the surface.

(2) EC machining reduces the standard deviation. This emphasizes that to study the effect of a variable on fatigue, the specimens should be EC machined for obtaining bonafide results, which can be compared without incorporating surface effects, thus revealing the effect of the variable alone.

(3) Ultrasonics, as a post ECM surface conditioning process can restore fatigue properties with the added advantage that complex shapes can be treated with ease. It can be easily controlled to give reliable, repetitive results.

Eventhough the EC machining appears to be satisfactory, if suitably controlled and followed by a surface conditioning treatment such as ultrasonics, there appears to be a need for more research in this area. The uncovering of inclusions in machining can result in significant stress raisers; the best control for this is a procurement control for the steel and not a machining control.

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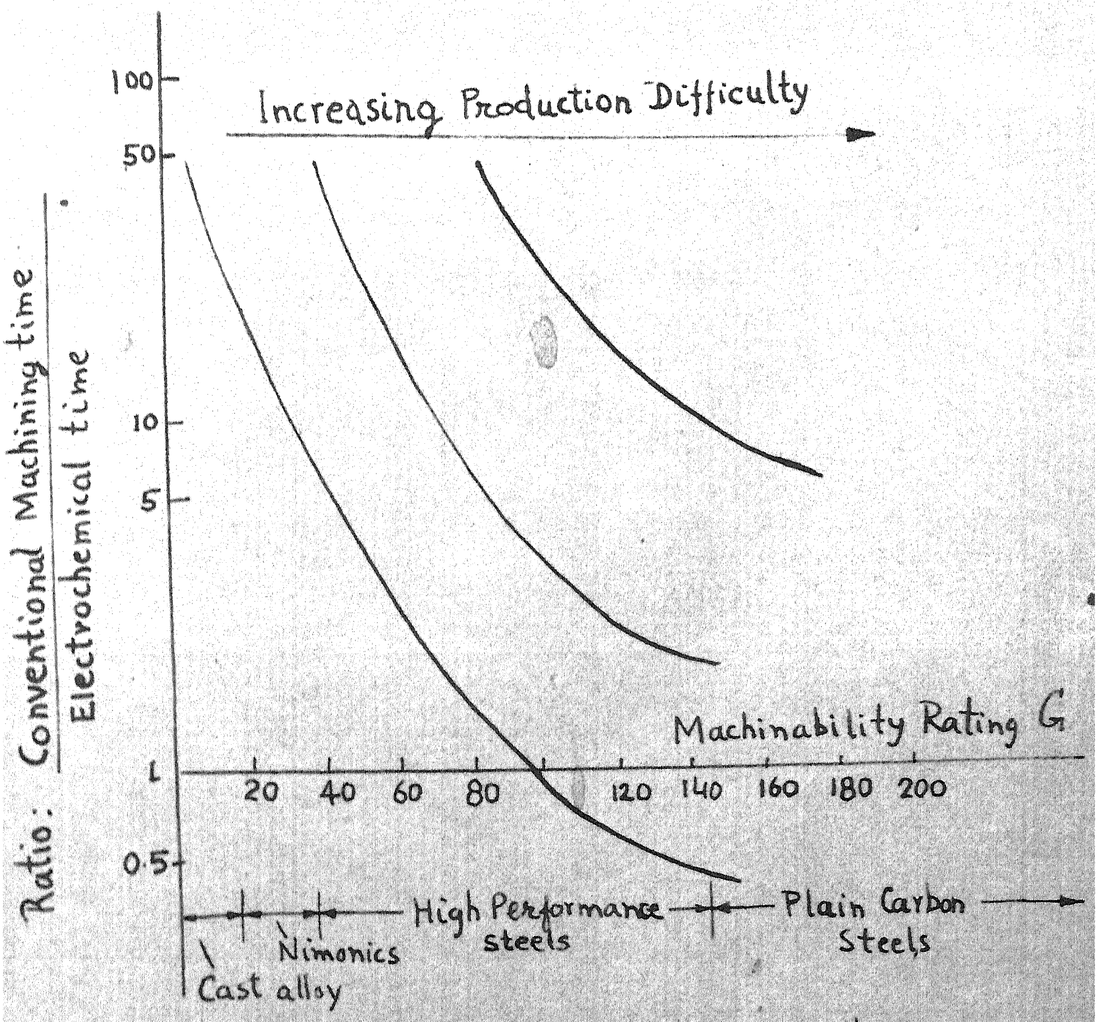

Fig-1. Whether or not ECM is economic depends upon the complexity of workpiece shape and the difficulty of machining the workpiece material.

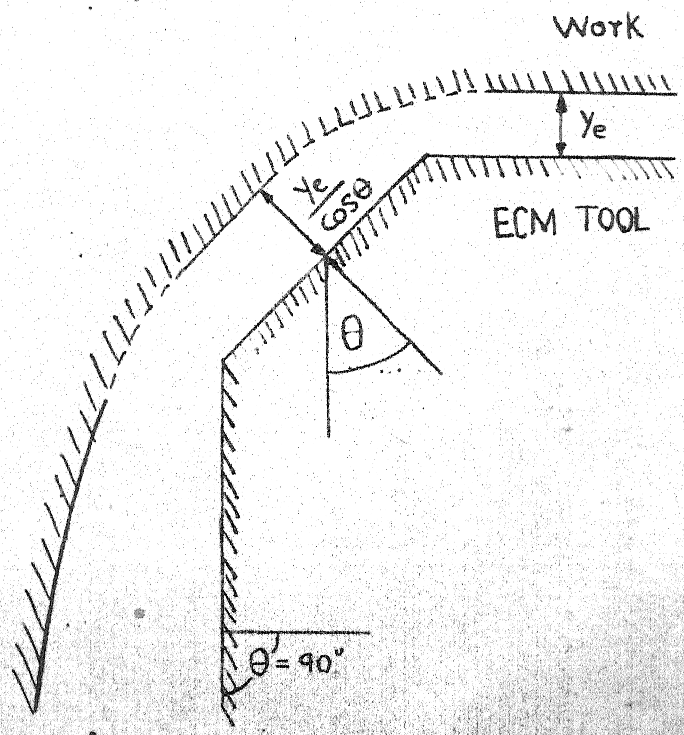

Fig-2. The equilibrium gap for three adjascent regions on a ECM tool which are inclined at angles 0, θ and 90°.

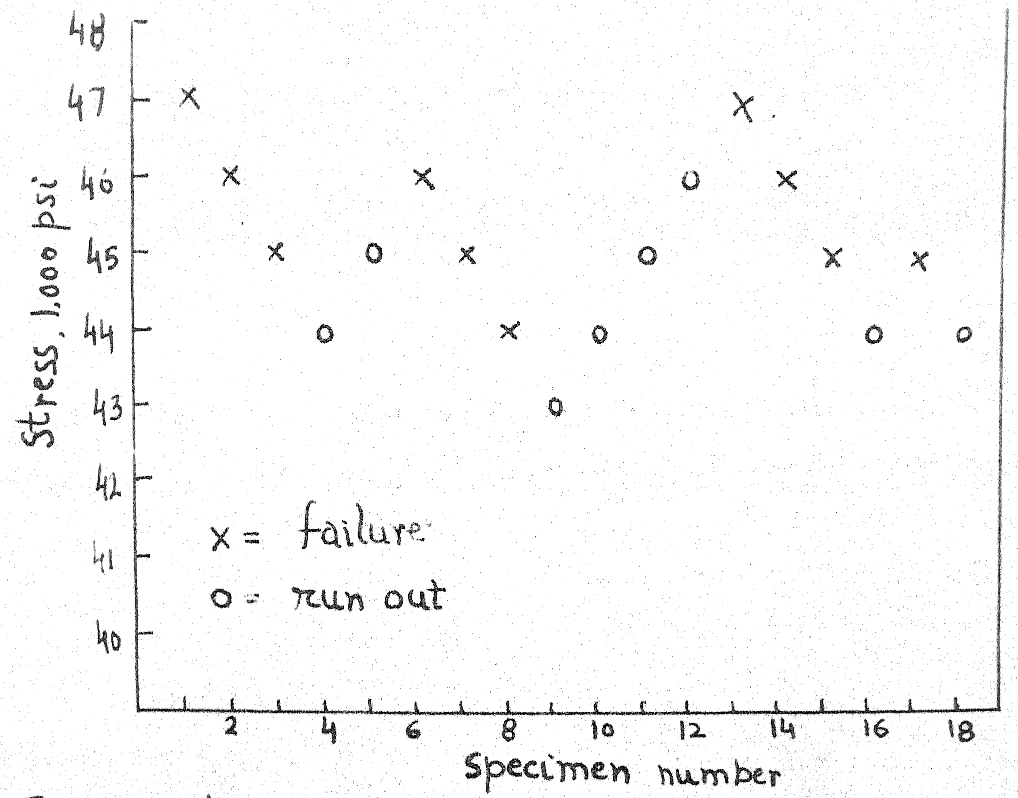

Fig-3. Staircase testing sequence for determination of Fatigue limit

Table-1

Method of analysing staircase data

Stress psi	i	n_i run outs	in_i	$i^2 n_i$
46,000	3	1	3	9
45,000	2	2	4	8
44,000	1	4	4	4
43,000	0	1	0	0
		N = 8	A = 11	B = 21

d = stress increment = 1000 psi

X_0 = first stress level = 43,000 psi

$$\therefore \bar{X} = 43{,}000 + 1000\left(\tfrac{11}{8} + \tfrac{1}{2}\right) = 44{,}870 \text{ psi}$$

$$* \quad S = 1.620\,(1000)\left[\frac{8\times 21 - (11)^2}{8^2} + 0.029\right] = 1{,}240 \text{ psi}$$

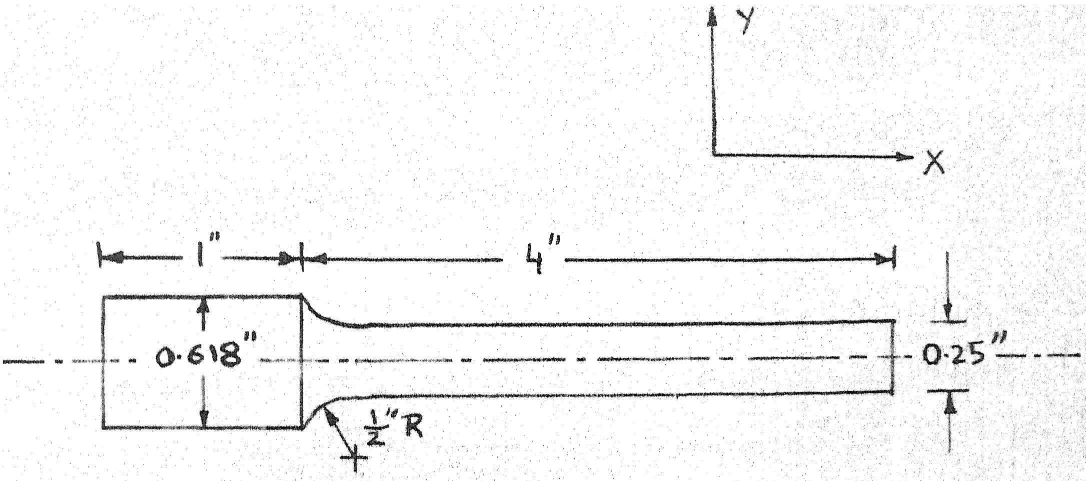

Fig-4. Cantilever Fatigue test specimen

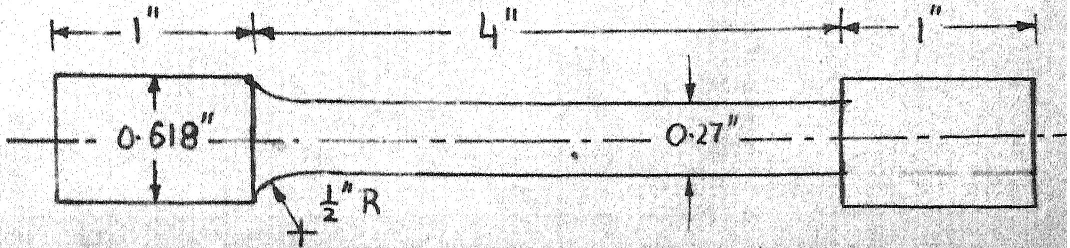

Fig-5. EC Cantilever Fatigue test specimen

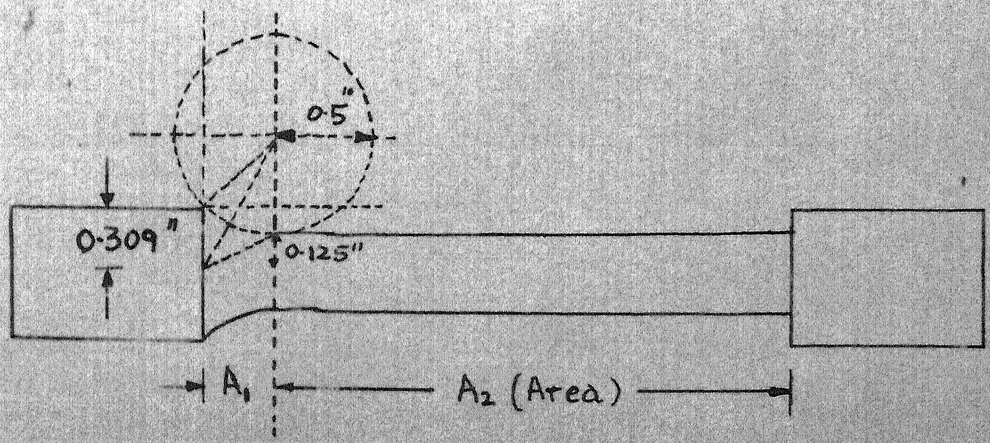

Fig-6. Calculation of EC machining area

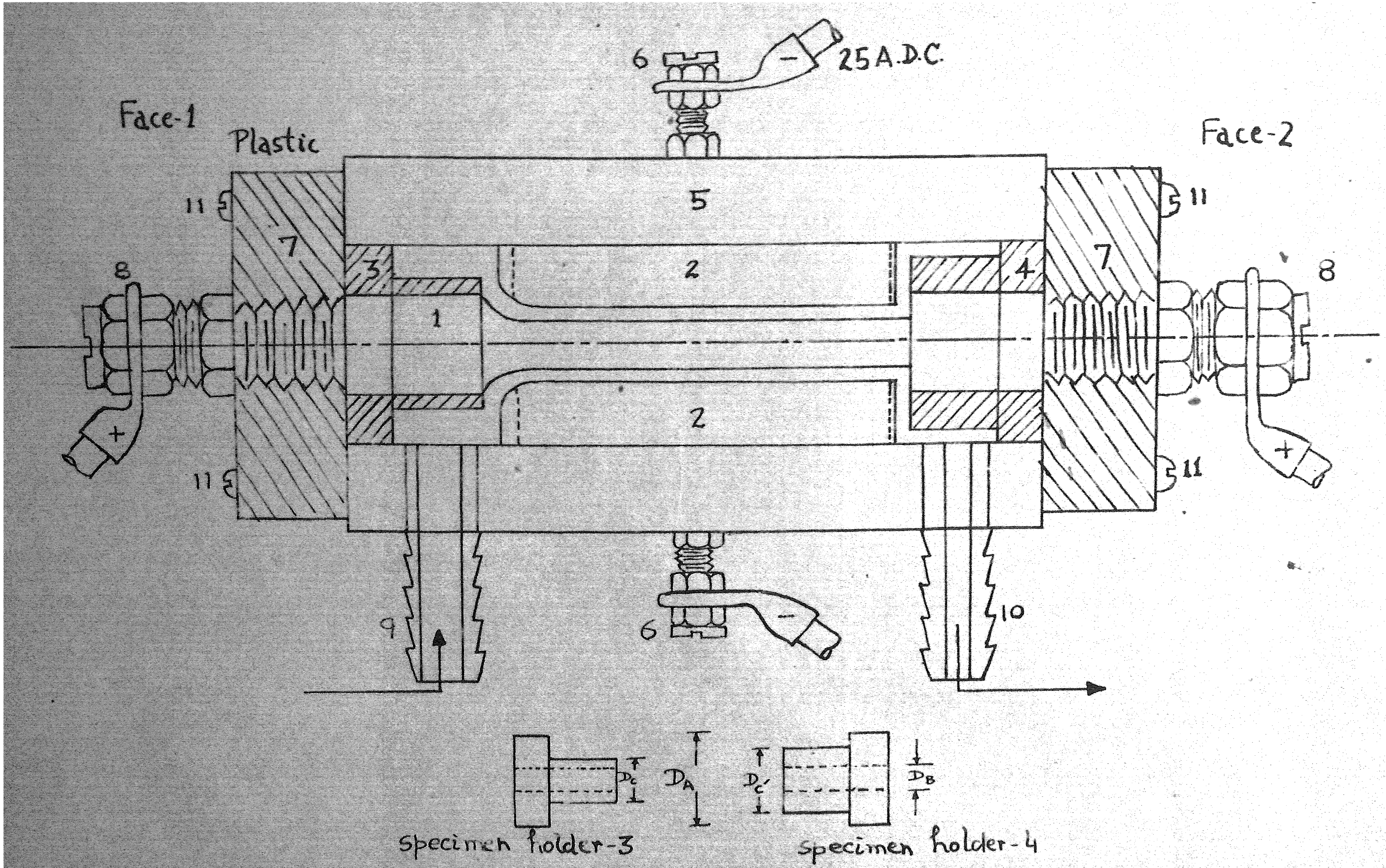

Fig-7. ECM static tooling for Cantilever fatigue test specimen

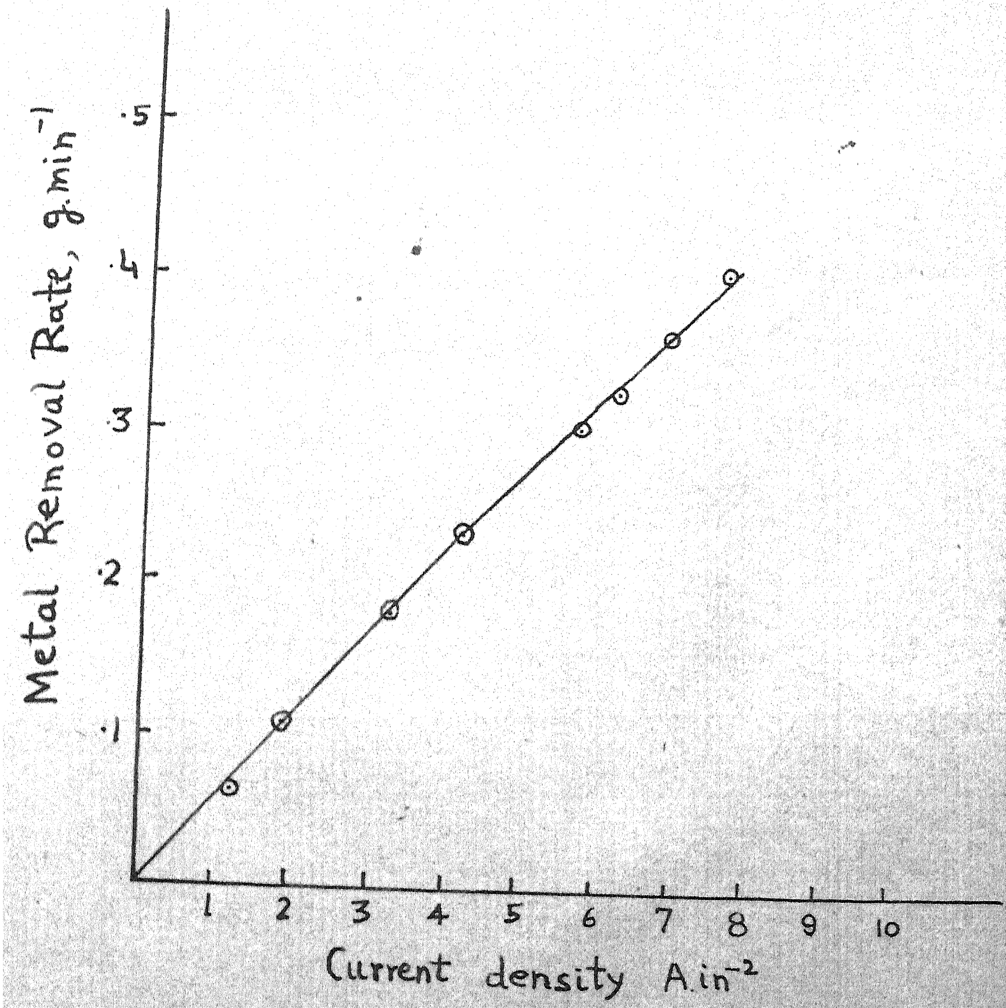

Fig-8. Effect of current density on metal-removal rate

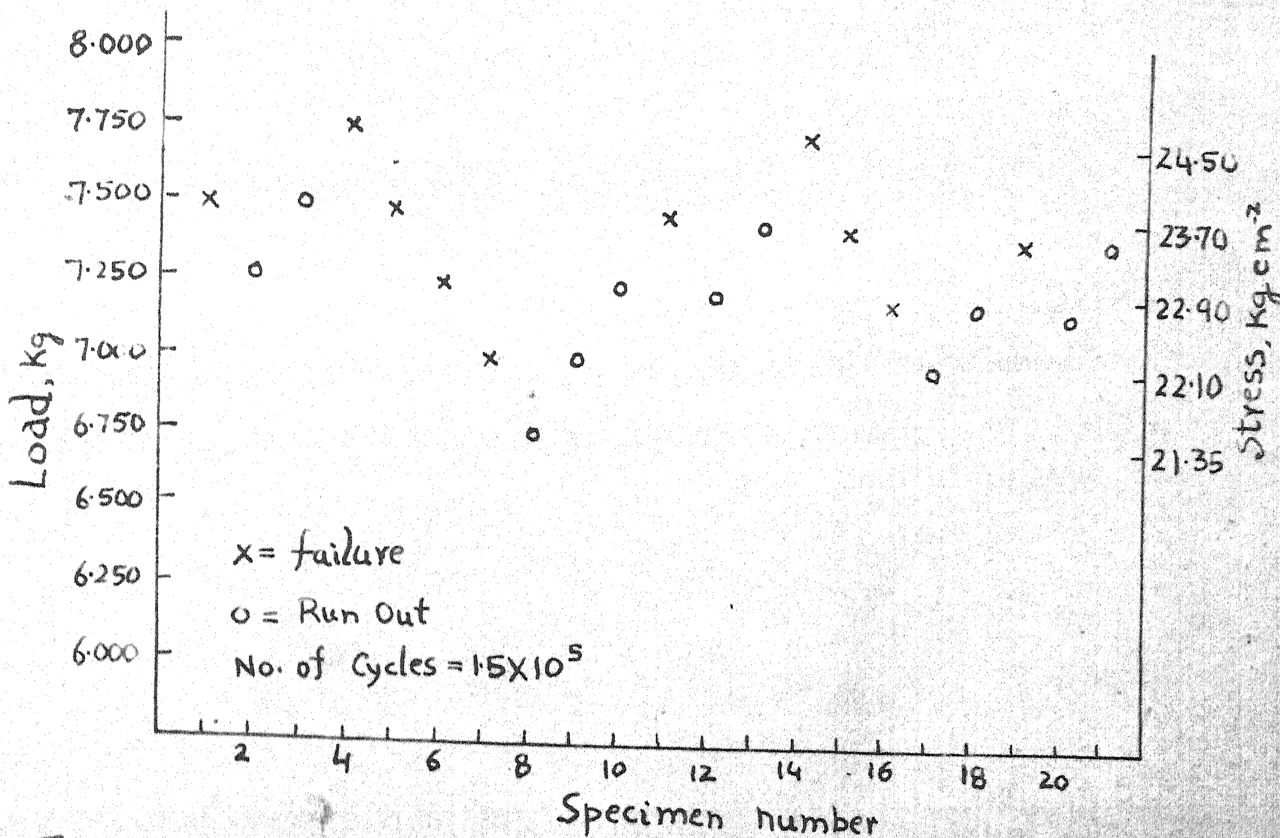

Fig.-9. Staircase testing sequence for determination of mean fatigue limit of lathe machined specimens

Table-3

Analysis of staircase data for lathe machined specimens

Stress $Kg.cm^{-2}$	i	n_i run outs	$i n_i$	$i^2 n_i$
23·70	3	3	9	27
22·90	2	5	10	20
22·10	1	2	2	2
21·35	0	1	0	0
		N = 11	A = 21	B = 49

d = stress increment = 0·79 $Kg.cm^{-2}$.

X_0 = first stress level = 21·35 $Kg.cm^{-2}$

$$\bar{X} = 21{\cdot}35 + 0{\cdot}79\left(21/11 + 1/2\right) = 23{\cdot}25\ Kg.cm^{-2}$$

$$S = 1{\cdot}620(0{\cdot}79)\left[\frac{11\times 49-(21)^2}{11^2} + 0{\cdot}029\right] = 1{\cdot}072\ Kg.cm^{-2}$$

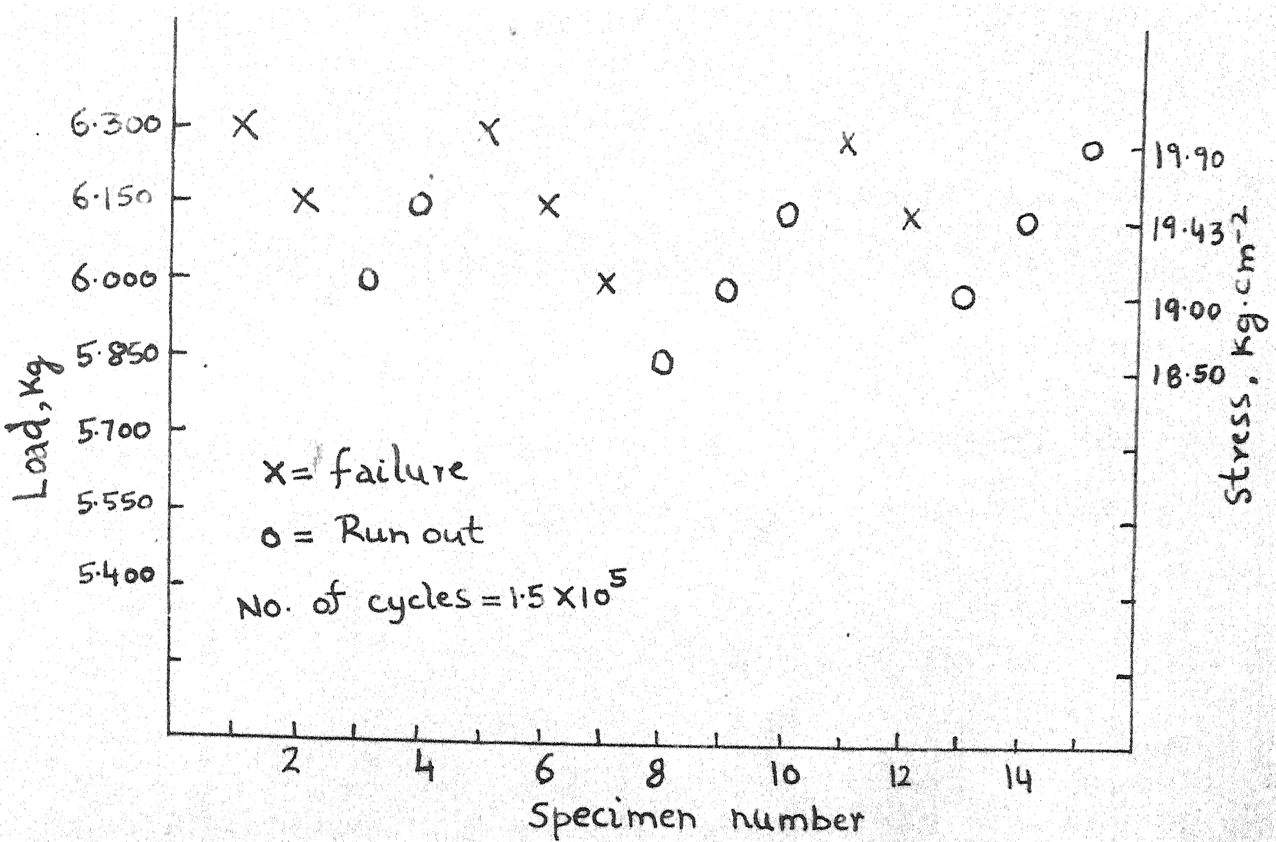

Fig-10. Staircase testing sequence for determination of mean fatigue limit of EC machined specimens

Table-4

Analysis of Fatigue data for EC machined specimens

Stress $Kg \cdot cm^{-2}$	i	n_i run outs	in_i	$i^2 n_i$
19·90	3	1	3	9
19·43	2	3	6	12
19·00	1	3	3	3
18·50	0	1	0	0
		N = 8	A = 12	B = 24

d = Stress increment = 0·47 $Kg \cdot cm^{-2}$

X_0 = first stress level = 18·50 $Kg \cdot cm^{-2}$

$$\bar{X} = 18{\cdot}5 + 0{\cdot}47\left(12/8 + 1/2\right) = 19{\cdot}44 \; Kg \cdot cm^{-2}$$

$$S = 1{\cdot}620\,(0{\cdot}47)\left[\frac{8 \times 24 - (12)^2}{8^2} + 0{\cdot}029\right] = 0{\cdot}59 \; Kg \cdot cm^{-2}$$

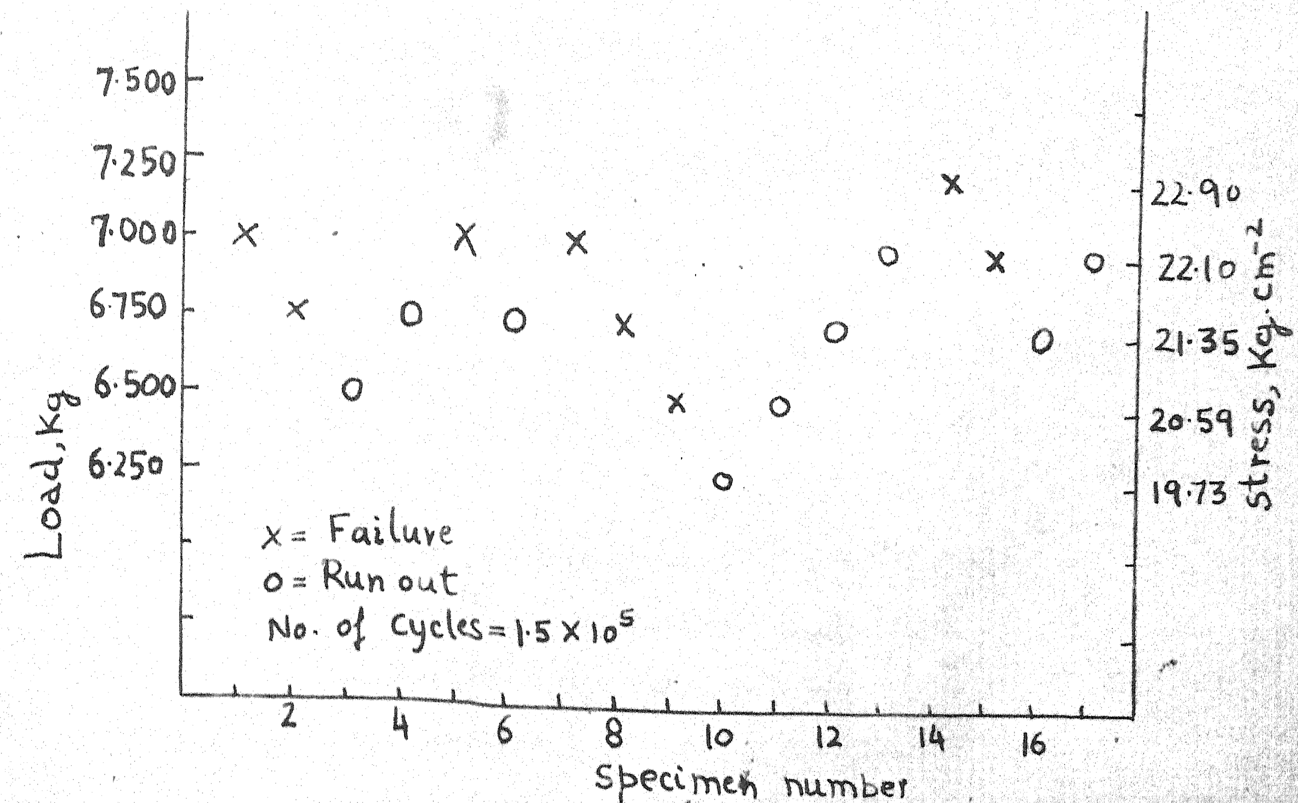

Fig-11. Staircase testing sequence for determination of mean fatigue limit of EC machined + Ultrasonically treated specimens

Table-5

Analysis of staircase data for ECM + Ultrasonically treated specimens

stress Kg. cm^{-2}	i	n_i run outs	in_i	$i^2 n_i$
22.10	3	2	6	18
21.35	2	4	8	16
20.59	1	2	2	2
19.73	0	1	0	0
		N = 9	A = 16	B = 36

d = stress increment = 0.79 Kg.cm^{-2}

X_0 = first stress level = 19.73 Kg.cm^{-2}

$$\bar{X} = 19.73 + 0.79\left(16/9 + 1/2\right) = 21.53 \text{ Kg.cm}^{-2}$$

$$S = 1.620\,(0.79)\left[\frac{9 \times 36 - (16)^2}{9^2} + 0.029\right] = 1.112 \text{ Kg.cm}^{-2}$$

"Man of the Future, what shall be
The life on Earth that you shall see?
What strange new facts the years will show?
What wonders rare your eyes shall know?
To what new realms of marvel, say,
Will conquering science war its way?"

- Bennett